Investigation of divertor operation for Japanese DEMO under low density SOL and large power exhaust of P_{sep}/R ~30 MW/m level

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This talk will present

1. Introduction:
   JA-DEMO design and power exhaust concept

2. Divertor power exhaust simulation for JA DEMO

3. Divertor operation in low SOL density

4. note: Heat flux profiles at SOL and target

5. Summary

1. JA-DEMO design and power exhaust concept

Major radius: 8.5m, Fusion power: 1.5GW-level, steady-state (year-long)

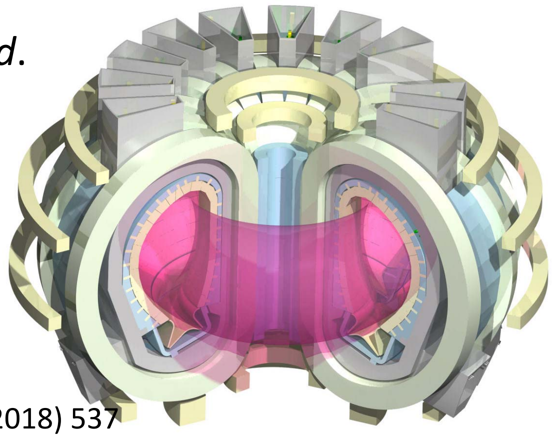
Influence of impurity seeding on original JA DEMO design (System code prediction) [1,2]:

- Fusion power is reduced <1.5GW due to fuel dilution.
- Higher HH-factor (~1.5) is required to maintain W_{th} and β_N.

⇒ Proposal of increasing I_p, P_{fus} **with κ_{95}** for the same R_p , a_p and q_{eff} without requesting higher plasma performance of HH_{98y2}>1.3.

- *Conducting shell (control of vertical stability) is improved.*

Japan DEMO (steady-state)



	Parameters	JA DEMO [3] (←[1]) high-κ &Seeding	ITER (inductive)
Size & Configuration	**R_p / a_p (m)**	**8.5 / 2.42**	6.2 / 2.0
	A	3.5	3.1
	κ_{95}	**1.75** (←1.65)	(1.70)
	q_{95}	4.1	3
	I_p (MA)	**13.5** (←12.3)	14
	B_T / B_T^{max} (T)	5.94 / 12.1	5.3 / 12
Absolute Performance	Operation	**Steady-state**	~400 s
	P_{fusion} (MW)	**1694** (←1462)	500
	P_{gross} (MWe)	**588** (←507)	--
	P_{aux} (MW)	**96** (←84)	73
	Q	18	10
Normalized Performance	HH_{98y2}	1.3	1.0
	β_N	3.4	1.8
	f_{BS}	0.6	0.15
	n_e/n^{GW}	1.2	~0.9

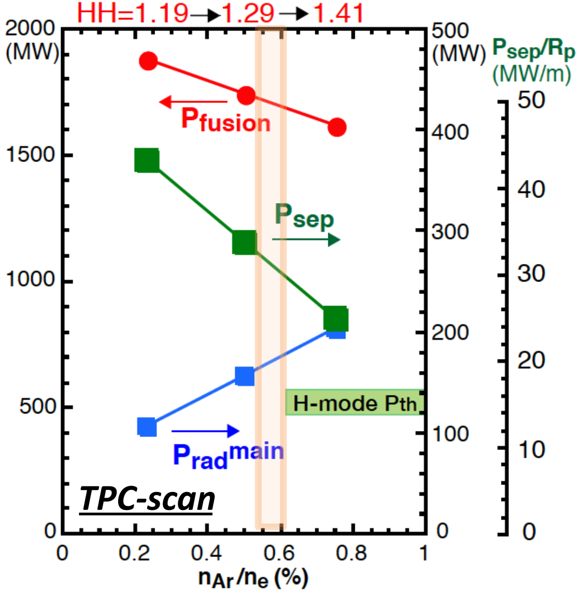
[1]Sakamoto, et al. IAEA FEC 2014,
[2]Tobita, et al. Fusion Sci. Technol. 72 (2018) 537
[3]Asakura, et al. Nucl. Fusion 57 (2017) 126050

Power exhaust and Plasma performance in impurity seeding

- **JA-DEMO:** System-code predicts that plasma performance of HH_{98y2}~1.3, β_N~3.4 , f_{BS}~0.6 in Ar seeding (n_{Ar}/n_e~0.6%) required for the steady-state operation is obtained by increasing P_{fus}(1.7GW), I_p (13.5MA), n_e($8.6 \times 10^{19} m^{-3}$) and κ_{95} (1.75).

⇒ $f_{rad}^{main} = P_{rad}^{main}/P_{heat}$~0.4: slightly larger than ITER ⇒ Reducing P_{sep} than original (still $2 \times P_{LH-th}$)

JA DEMO: higher κ_{95}(1.75) & Ar seeding [3]



	Parameters	JA DEMO[3] Increase κ_{95}&seeding	JA DEMO1[1,2] Original
Density	**line-n_e^{main} ($10^{20}m^{-3}$)**	**0.86**	0.78
	n^{GW} ($10^{20}m^{-3}$)	0.73	0.67
Power exhaust	n_{imp}^{main}/n_e (%)	0.6 (Ar)	0.25 (Ar)
	P_{fusion} (MW)	1694	1462
	P_{aux} (MW)	96	84
	P_{heat} (MW)	**435**	**376**
	P_{rad}^{main} (MW)	177	82
	P_{rad}^{main}/P_{heat}	**0.41**	**0.22**
	P_{sep} (MW)	**258**	**294**
	P_{sep}/R_p(MWm^{-1})	**30**	**35**

[4] ***P_{LH-th}*** : Martin et al J. Phys.: Conf. Ser. (2008).

Power exhaust and divertor concept of JA and EU DEMOs

Divertor power handling is determined by requirements of f_{rad}^{main} and plasma performance.

Common view of Power exhaust scenario in JA and EU:

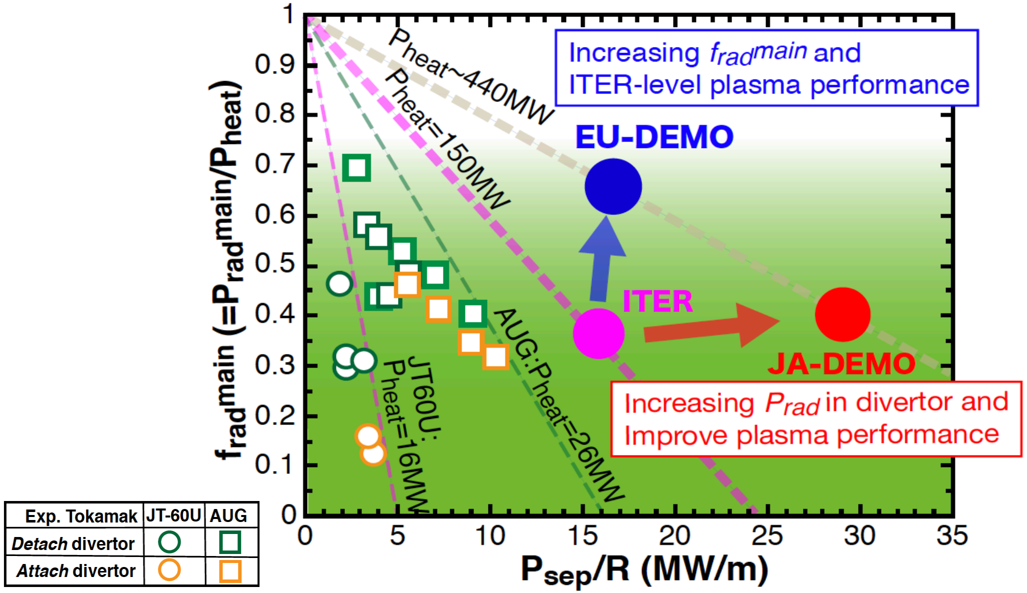
- High radiation fraction ($f_{rad} = P_{rad}/P_{heat}$~80%) is required, while f_{rad}^{main} and $f_{rad}^{sol+div}$ are different:

Note: EU-DEMO (pulse): ITER-level performance (HH_{98y2}~1.1, β_N~2.6) in Xe&Ar seeding achieves $P_{el,net}$~0.5GW ($P_{el,gross}$~0.91GW)

⇒ *increasing* f_{rad}^{main} ~0.65 in order to reduce P_{sep}~1.2x$P_{LH\text{-}th}$ [5] Wenninger, et al. Nucl. Fusion 57 (2017) 016011.

Another common issue: *Line-ave.* n_e is lower than ITER ($1\text{x}10^{20}m^{-3}$) due to lower n^{GW}.

- Plasma detachment at low n_e^{sep} ~n_e^{ped}/3 ($2\text{-}3\text{x}10^{19}m^{-3}$) is required.



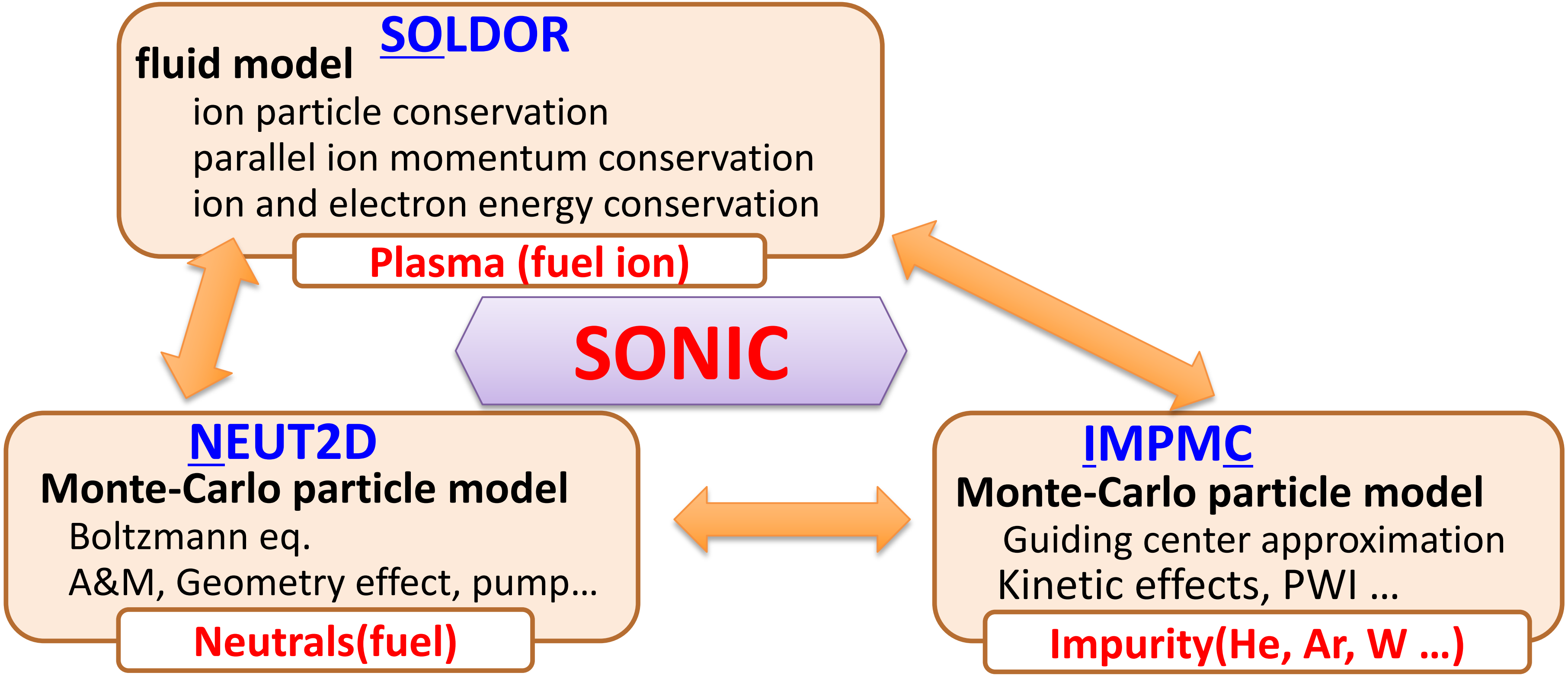
JT-60U: Asakura, et al. Nucl. Fusion (2009). AUG: Kallenbach, et al., Nucl. Fusion (2015).

	Parameters	JA DEMO[3]	EU DEMO1[5]
Density	**line-n_e ($10^{20}m^{-3}$)**	**0.86**	0.87
	n^{GW} ($10^{20}m^{-3}$)	0.73	0.72
Power exhaust	n_{imp}^{main}/n_e (%)	0.6 (Ar)	0.039 (Xe)
	P_{fusion} (MW)	1694	2037
	P_{aux} (MW)	96	50
	P_{heat} (MW)	**435**	457
	P_{rad}^{main} (MW)	177	306
	P_{rad}^{main}/P_{heat}	**0.41**	0.67
	P_{sep} (MW)	**258**	154
	P_{sep}/R_p (MWm^{-1})	**30**	17

[6] Asakura, et al. Fusion Eng. Des. 136 (2018) 1214.

SONIC code: a suite of integrated divertor codes
Applying to simulate JT-60U experiments/JT-60SA and JA DEMO design

SONIC code consists of **SOLDOR** (fluid transport simulation of plasma), **NEUT2D** (kinetic transport simulation for neutrals), and **IMPMC** (kinetic transport simulation for intrinsic/seeded impurity).



SONIC references: [7] K. Shimizu, et al., J. Nucl. Mater. 2003, [8] H. Kawashima, et al. J. Plasma Fusion Res. 2006

2. Divertor power exhaust simulation for JA DEMO: (Reference case) Divertor leg length: L_{div}=1.6m, P_{sep}~235MW

- **At core-edge boundary r/a=0.95**: exhausted power (P_{out}= 250 MW), particle (Γ_{out}^{D+}=1x10^{22} s^{-1})
- Covering the connecting SOL between inner and outer divertors: $r^{mid} \leq$ 3.2 cm.

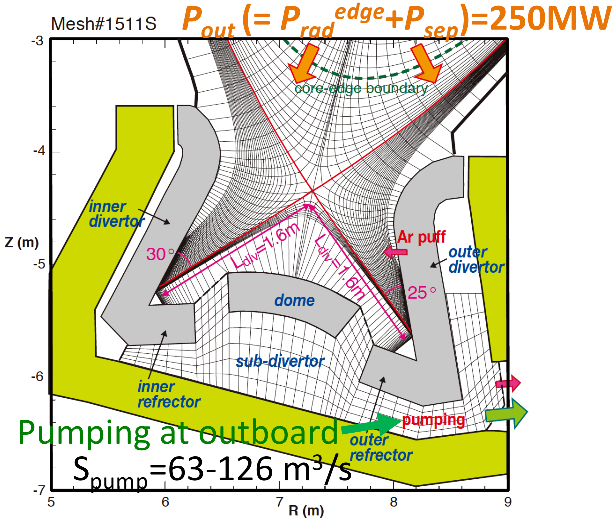
Divertor leg is 1.6 m（1.6 times longer than ITER): it is reduced from 2 m case (2015)

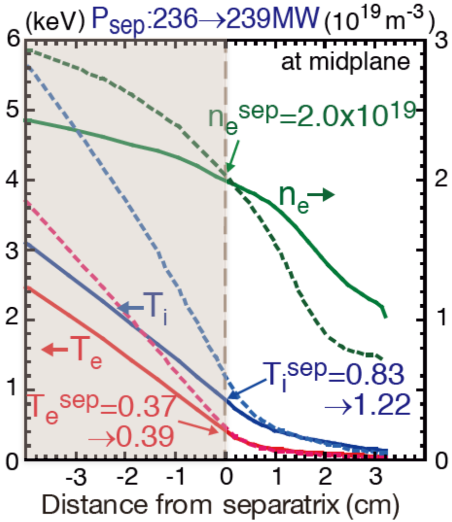
T_e^{sep} & T_i^{sep} increase to 0.37 & 0.83 keV, which are 2-3 times larger than ITER

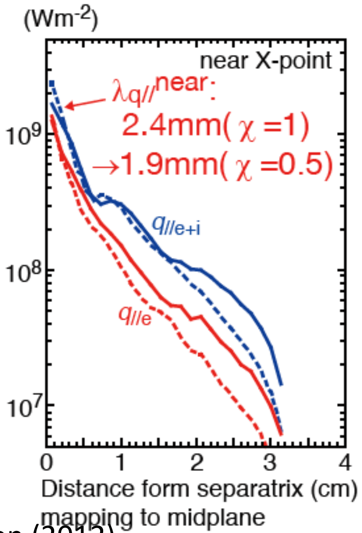
⇒ $\lambda_{q//}$ = 2.4mm for the same χ (=1m^2/s) and D (=0.3m^2/s) as ITER ($\lambda_{q//}$ = 3.4 mm)[9].

Reduction to half values（χ = 0.5m^2/s, D = 0.15m^2/s） ⇒ $\lambda_{q//}$ is reduced to 1.9mm.

- $q_{//}$ profile is still *wider than Eich's scaling*[10] (~1mm) and *Goldston's model*[11] (~1.5mm).







[9] Kukushkin, et al. J. Nucl. Mater. (2013). [10] Eich, et al. Nucl. Fusion (2013). [11] R. Goldston, Nucl. Fusion (2012).

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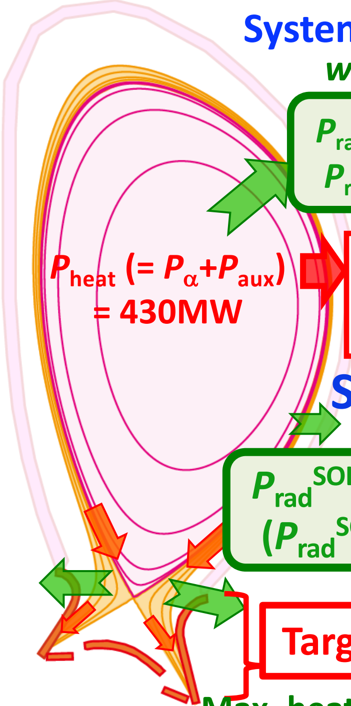
Reference scenario of the power exhaust (SONIC)
D gas puff & Ar seeding ⇒ $P_{rad}^{SOL} + P_{rad}^{div}$=186MW

Inner target: Full detachment ($T_{e,i}$~1eV in all r)
Outer target: radiation peak becomes closer to the target
⇒Partial detachment (r < 14cm)

$(P_{rad}^{SOL+div}+P_{rad}^{main})/P_{heat}$ = 0.84

System code (TPC) output
with n_{Ar}/n_e~0.6%

P_{rad}^{main} = 177MW:
P_{rad}^{main}/P_{heat} = 0.41



P_{sep}= 253MW(TPC)
~235MW(SONIC)

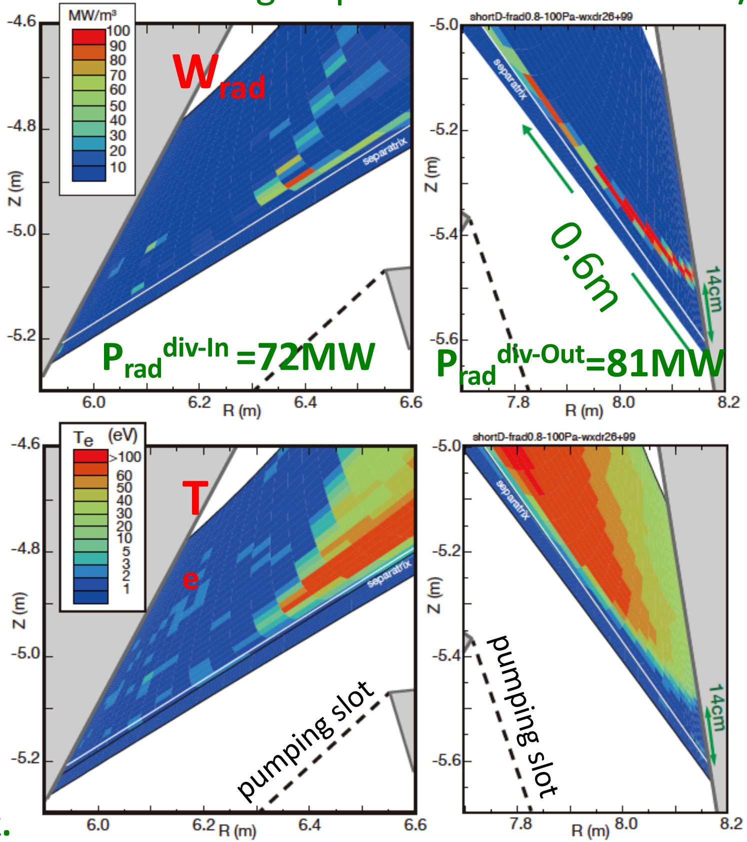
SONIC simulation

P_{rad}^{SOL}+P_{rad}^{div} = 186MW:
$(P_{rad}^{SOL} +P_{rad}^{div})/P_{heat}$= 0.43

Target heat load (5-8 MWm^{-2})

Max. heat load: 10 MWm^{-2} by W&Cu-alloy heat sink.

Increasing D puff rate to 5.3x10^{22} D/s,
while reducing Ar puff rate to 3.4x10^{20} Ar/s



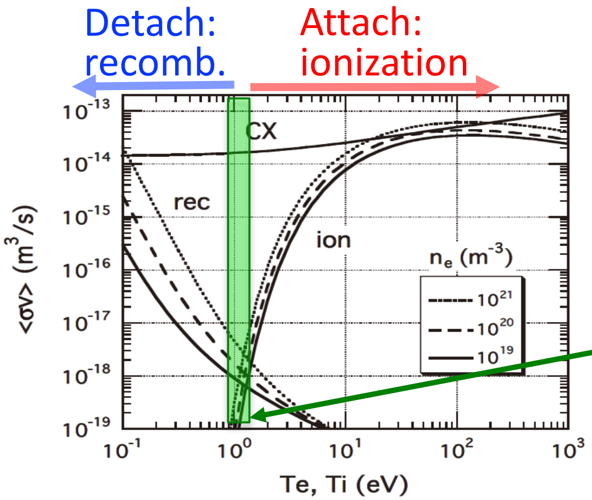
Detachment plasma is produced: q_{target} is less than 10MWm^{-2}
"Partially attached" is produced in the outer divertor

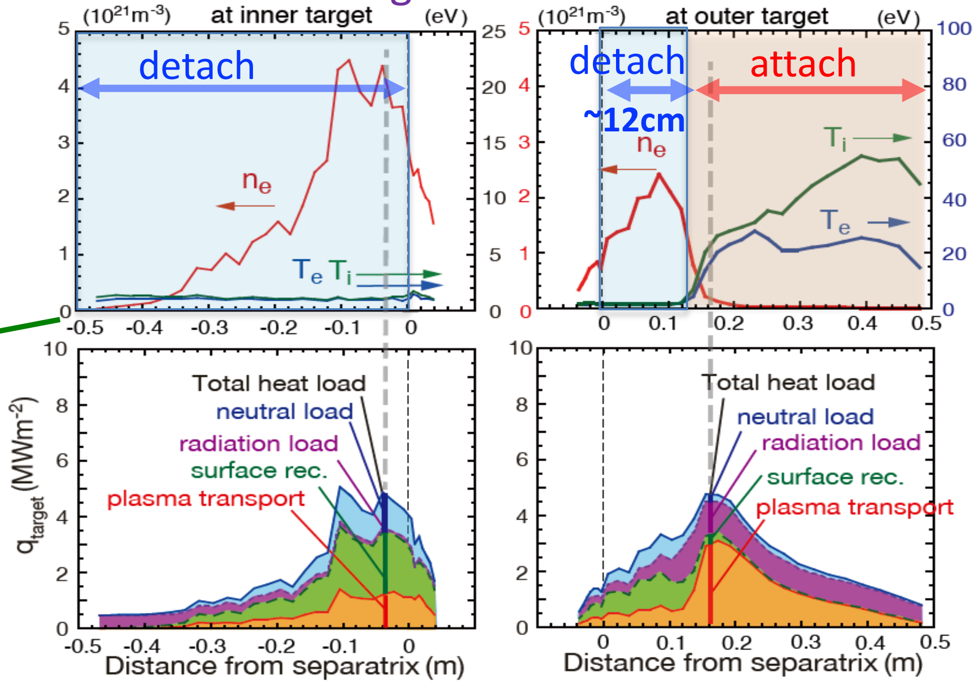
Inner target: peak q_{target} ~5 MWm^{-2}, where ionization still occurs at $T_e = T_i$ ~1 eV.

- Surface recombination is a dominant ⇒ Volume-recombination is not significant.
  Significant reduction in ion flux (seen in experiments) is not modelled quantitatively.

Outer target: peak q_{target} ~5 MWm^{-2} is seen at "*attached*" region (r_{target} > 12cm).

⇒ plasma heat load is dominant, and radiation load is also large.





Other insufficient modeling:

- *Elastic collision,*
- *Plasma transport: blobs, drifts,*
- *Photon absorption, etc.*

3. Divertor operation in low SOL density (n_e^{sep} = 2-3x10^{19}m^{-3})

Heat load can be reduced less than engineering restriction (q_{target} ≤10MWm^{-2})

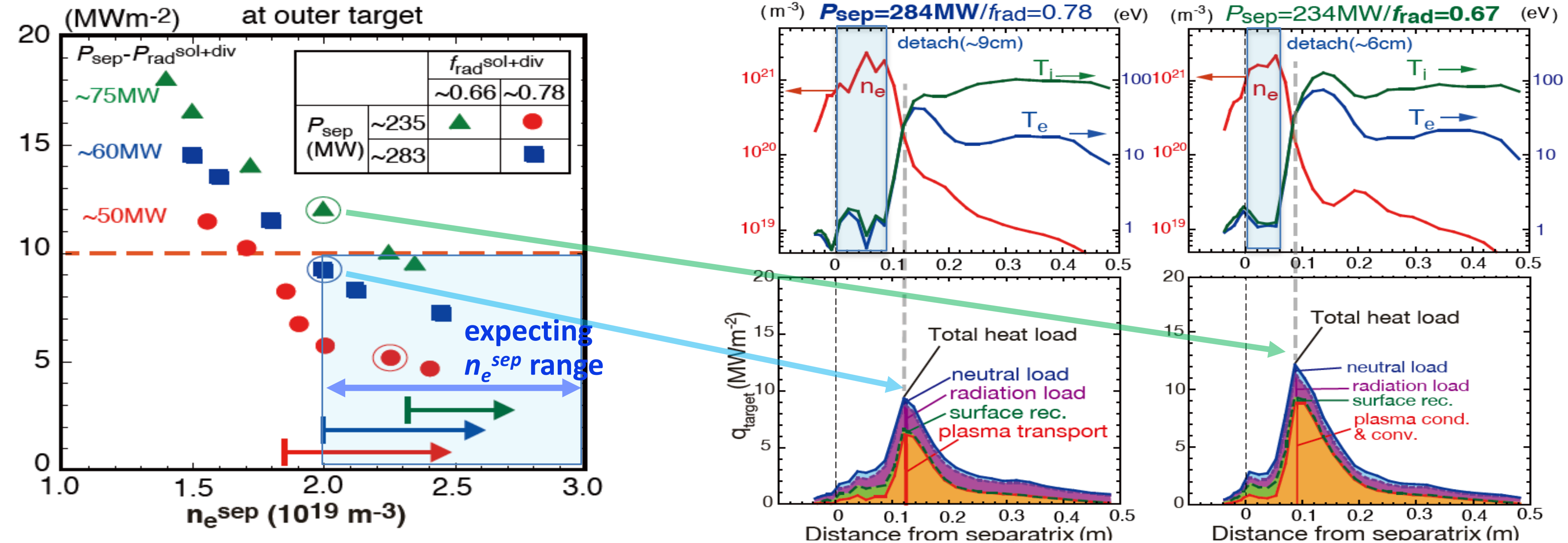
Reference: P_{sep} = P_{out}-P_{rad}^{edge} ~235MW & $f_{rad}^{sol+div}$=(P_{rad}^{sol}+P_{rad}^{div})/P_{sep} ~0.78, and

Severe cases: high P_{sep}~283MW ($f_{rad}^{sol+div}$~0.78) and **low $f_{rad}^{sol+div}$~0.66 (P_{sep}~236MW) are studied.**

Decresing *deatchment width*, and increasing T_i, T_e *at the attached plasma*.

⇒ q_{target} is increased, and a margin of the power handling (≤ 10 MWm^{-2}) is decreased.

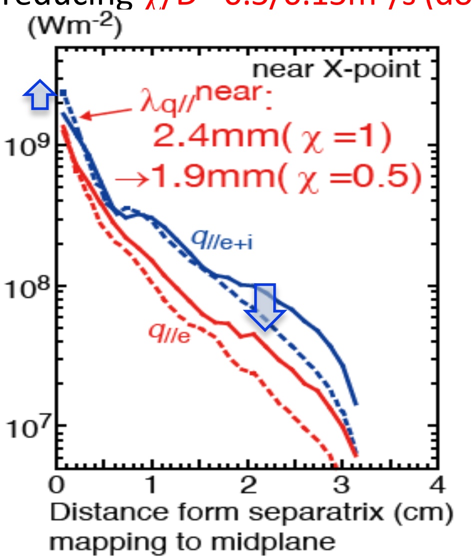
low n_e^{sep} (2-3x10^{19}m^{-3}) is acceptable, but higher n_e^{sep} is required for the low $f_{rad}^{sol+div}$ case.

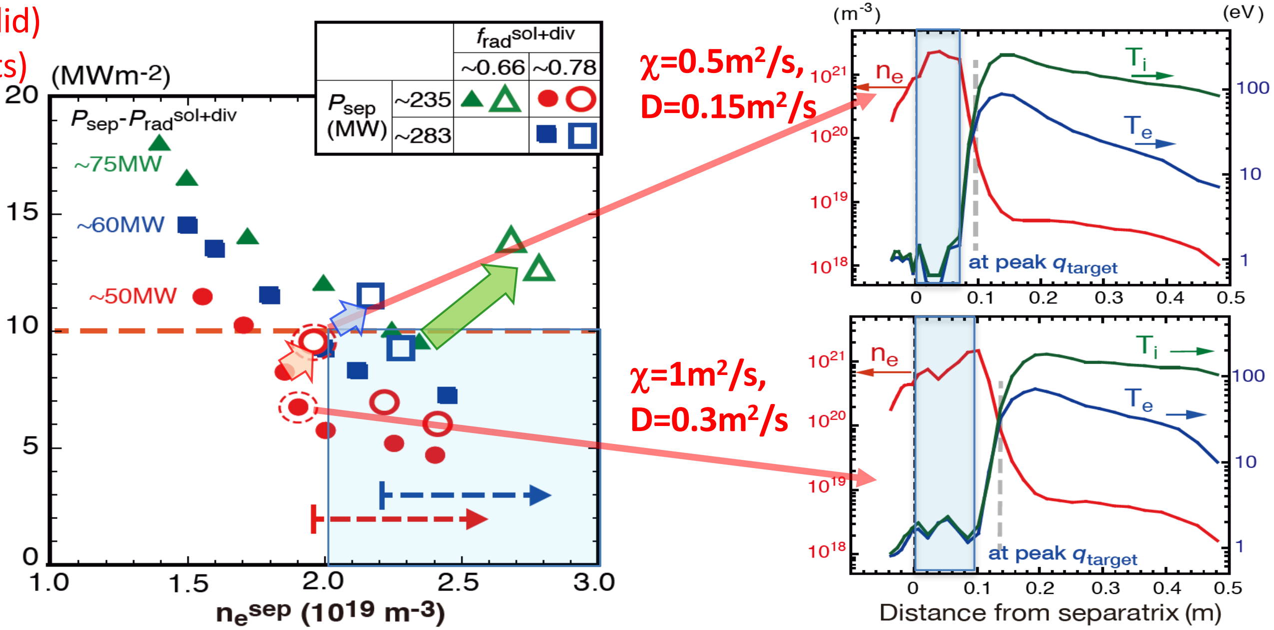


Influence of plasma diffusion on heat flux and plasma profiles: Increase in q_{target} is large in *Low* $f_{rad}^{sol+div}$ (0.66) case than *high* $f_{rad}^{sol+div}$ (0.78)

- Simulations with reducing χ and D to 1/2 ($\chi_e = \chi_i = 0.5 m^2/s$, $D = 0.15 m^2/s$)
  $\lambda_{qe//}$ is reduced from 2.4 to 1.9 mm, but still larger than Eich's B_p-scaling (1.1 mm).
- Detachment region is reduced from 10 to 7 cm ⇒ peak-q_{target} is increased.
- Divertor heat load in High $f_{rad}^{sol+div}$ (~0.78) : Reference and High P_{sep} cases are still acceptable, but divertor operation in the Low n_e^{sep} range (2-3x10^{19} m^{-3}) is difficult for the low $f_{rad}^{sol+div}$ case.

$q_{e//}$ and $q_{e+i//}$ for χ/D =1/0.3 m²/s (solid)
and reducing χ/D =0.5/0.15m²/s (dots)





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Reduction in T_e^{div} and T_i^{div} at attached area is required

Reduction in T_e & T_i of attached plasma is necessary such as "pronounced detachment: AUG"

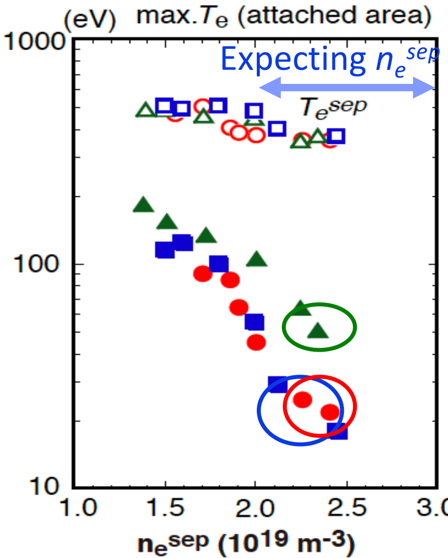
Partially detachment for *Reference* and *high P_{sep}* cases: Reduction in T_e^{div} to 20-30 eV is expected in the low n_e^{sep}. ⇒ Evaluation of net-erosion rate and improvement of its accuracy are required.

For the low $f_{rad}^{sol+div}$, decreasing detachment width, and reduction in T_e^{div} is small.

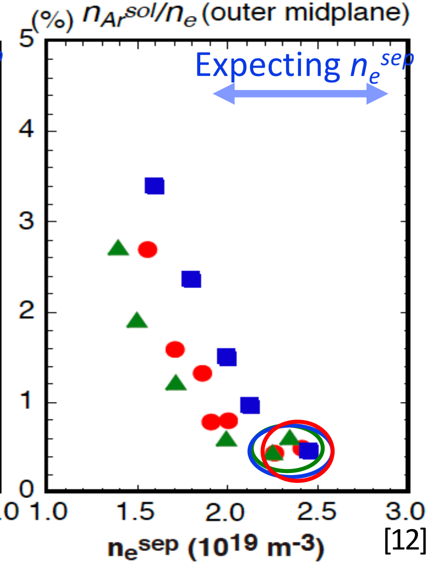
Experiment data and Modeling of erosion & transport (finite-Larmor effect[12]) must be improved.

Impurity concentration in SOL ($c_{Ar}^{SOL}=n_{Ar}^{sol}/n_e^{sol}$) : Both Increasing $P_{rad}^{sol+div}$ and Controlling the core plasma dilution are required ⇒ c_{Ar}^{SOL} (0.4-0.6%) is comparable to c_{Ar}^{main} in system code.

Peak T_e at attached region



Ar concentration at SOL



Simple estimation of net-erosion with 90% re-deposition

- Net erosion (Δd) becomes a half of W-width (d:5mm), if T_e^{div}~20eV at attached area.

Net erosion/year(mm)	T_e=5eV	10eV	20eV
DEMO (steady state)	0.15	1	**2.5**
ITER(400s, 2000 shots)	0.004	0.026	**0.064**

attach plasma Γ_i~10^{23} m^{-2}s^{-1}, ~20eV <Z>=4, n_{Ar}/n_i =0.2%, **assuming net erosion: R_{net}=0.1**

Sputtering yield with Ar Y_iC_i ~4×10^{-4} (at 20eV) [13]

Δd **(mm)** = $4.95\times10^{-19} R_{net} * Y_iC_i * \Gamma_i * t$(year)

[12] Y. Homma, et al., Nucl. Mater. Energy. (2017). [13] A. Kallenbach, et al., J. Nucl. Mat. (2011).

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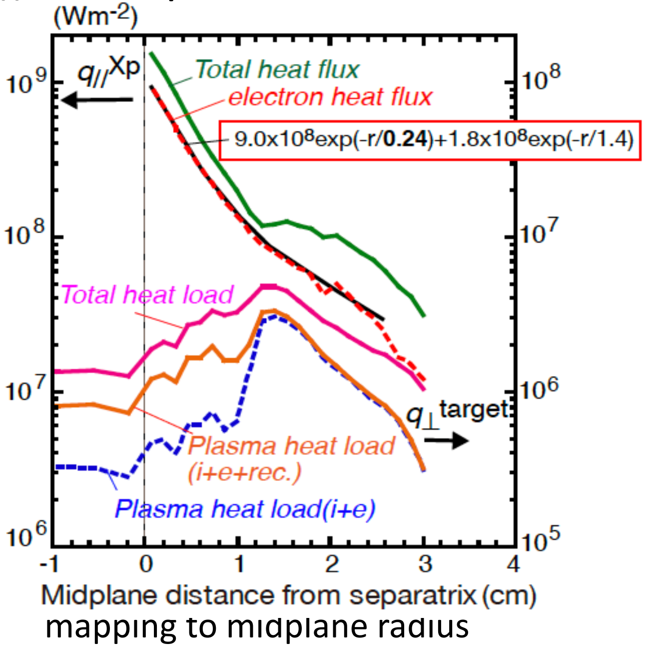
4. Heat flux profile at SOL and target

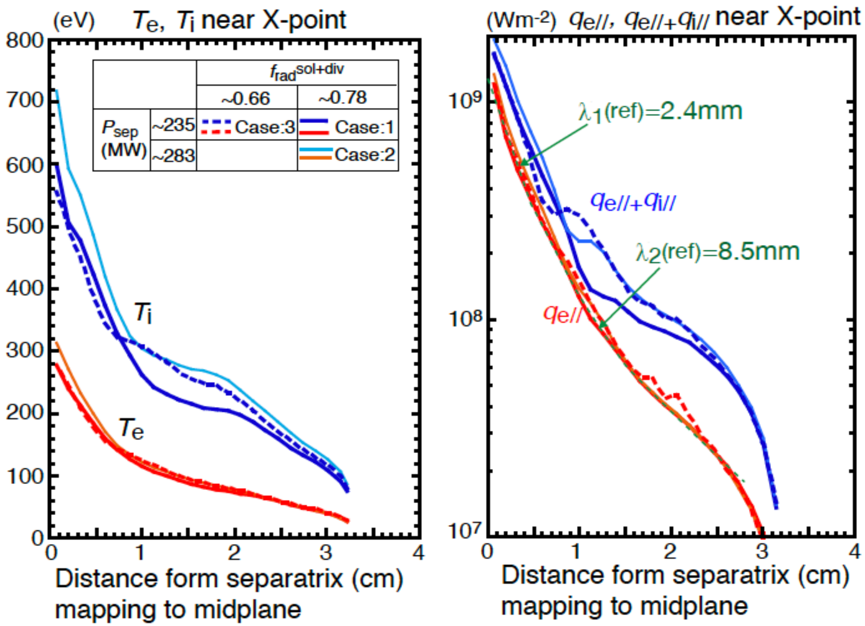
Large $q_{//}$ near separatrix is reduced in *the partially detached divertor*

- SOL heat flux near the separatrix (λ_q^{mid} = 2.4 mm at X-point) is reduced at the target.
- T_e and $q_{e//}$ profiles near X-point are similar for 3 cases (at the same n_e^{sep}~$2.0\text{x}10^{19}\text{m}^{-3}$)
  ⇔ *T_i in the outer flux surfaces* (r^{mid} = 8-20 mm) is increased for severe cases,
  and total $q_{//}$ is increased: convective transport may change.

$q_{//}$ near X_p vs $q_\perp$ at target (reference)



T_e, T_i and $q_{//}$ near X_p for 3 cases (same n_e^{sep})



Characteristics of heat load profiles in partial detached divertor applying Eich's convolution function, introducing detach-attach boundary (r_{det})

- Eich-fit was tied to apply to *thermal plasma* and *total heat load* *profiles*:
  Same flux expansion on target: f_x (=11-15) is given.
  Cross radius: s_0=0.011m (r_{cross}=0.14m) is fixed.
  e-folding length: λ_q^{mid} **is slightly decrease from 8 to 7 mm**
  Gaussian function: S^{mid} **is increased from 2.5 to 3.5 mm**
  Zero heat load: q_0 **is increased from 5.3 to 6.8 MWm^{-2}**
  and **Background heat load**: q_{BG} **= 1.1 MWm^{-2} is added**

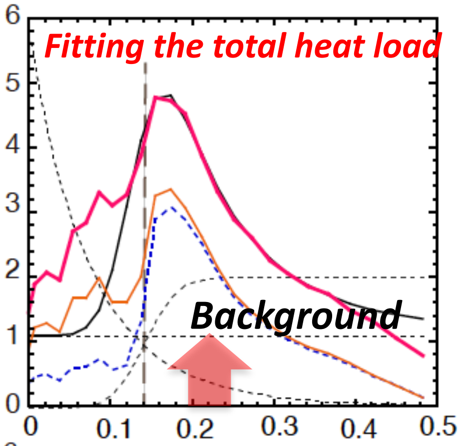
- Eich-fit can be applicable to *both thermal plasma* and *total heat loa profiles (in attached plasma region)*, while the fit function in the detached region (incl. the surface recomb., radiation, neutral loads) was not appropriate.

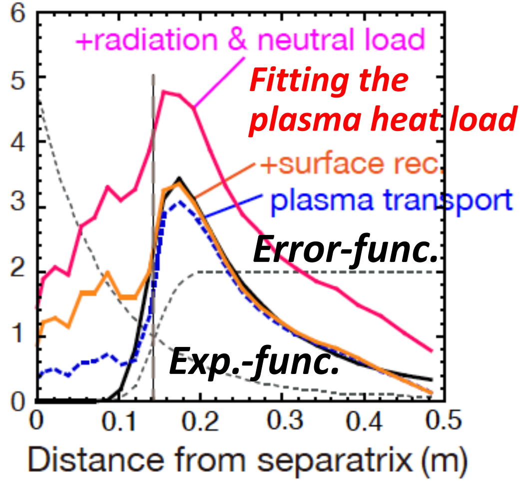
Eich-fit function: convolution of exponential and gaussian.

$$q(\bar{s}) = \frac{q_0}{2}\exp\left(\left(\frac{S}{2\lambda_q}\right)^2 - \frac{\bar{s}}{\lambda_q f_x}\right)\cdot \mathrm{erfc}\left(\frac{S}{2\lambda_q} - \frac{\bar{s}}{S f_x}\right) + q_{BG}$$

$$\bar{s} = s - s_0 = (R_{sep} - R)\cdot f_x$$

R_{sep} (0) $\Rightarrow R_{cross}$ (0.14m)





[14] T. Eich, et al. Nucl. Fusion 53 (2013) 093031. [15] T. Eich, et al. J. Nucl. Mater. 438 (2013) S72

5. Summary: Power exhaust and divertor design for JA DEMO

Recent progress of Japanese DEMO design and Divertor concept were summarized.

High plasma performance of HH_{98y2}~1.3, β_N~3.4, f_{BS}~0.6, n_e/n^{GW} ~1.2 is expected with $(n_{Ar}/n_e)^{main}$ = 0.6% by impurity (Ar) seeding (**P_{rad}^{main}/P_{heat}=0.41**, slightly larger than ITER).

- Divertor power handling of reference concept (P_{sep}~250 MW, P_{sep}/R ~29 MW/m) and under sever conditions (P_{sep}, $P_{rad}^{sol+div}/P_{sep}$, χ) was studied in the *expecting low SOL* n_e (~1/3x n_e^{main} =2-3x10^{19}m^{-3}).

Plasma performance in the long-leg divertor by SONIC simulation:

- Partial detachment (outer) was produced for $P_{rad}^{SOL+div}/P_{heat}$ = 0.43 ($P_{rad}^{SOL+div}/P_{sep}$= 0.78)
  ⇒ large $q_{//}$ near SOL (r^{mid} < 1 cm) can be reduced by the partial detachment, and peak-q_{target} at attached region is also reduced less than 10 MWm^{-2}, which was simulated under *sever conditions, i.e.* increasing P_{sep} by 20% or reducing $P_{rad}^{SOL+div}/P_{sep}$ by 10%.
- Heat flux profile reducing χ = 1 ⇒ 0.5 m^2/s: λ_q^{SOL} (~2mm) is still larger than Eich's scaling
  ⇒ Impact of reducing χ, particularly for smaller $P_{rad}^{SOL+div}/P_{sep}$, is serious.
- Net-erosion in the *partially attached area* (T_e=20-30eV) will be a critical life-time issue of W-target in year-long operation ⇒ improvement of W transport model is on going.
- Impurity concentration in SOL : c_{Ar}^{SOL}（0.4-0.6%）is so far comparable to c_{Ar}^{main} in system code.
  Increasing $P_{rad}^{sol+div}$ with controlling dilution of the core plasma is required.

Summary (2): Some issues in SONIC simulation and modelling

SONIC code (re-structuring to *Multi-Process Multi-Data*, i.e *multi-species*, renewing *plasma fluid-code including drifts*) and **modelling for DEMO plasma** (*erastic collision of atom and molecule, photon absorption, thermal force on impurity in low-collisional SOL*) are developped.

⇒ Power exhaust and divertor design, consistent with He exhaust, will be revised.

⇒ Restructure of the plasma fluid code (**SOLDOR in SONIC**) **incorporating drifts** is on going.

Improvement of simulation on the heat load profile *at the partial detachment* is necessary:

- Plasma modelling : distributions of diffusion coefficients, momentum loss process, etc.
- Empirical scaling of the detached heat load and the peak value will be used for design.

Control of radiation peak and detachment front *in the long-leg* is high priority issue:

- Impurity transport in SOL (low collision) - divertor (high collisional), and the shielding efficiency (thermal force vs friction force) are key issues to design the seeding scenario and divertor:

Classical formula of thermal force on impurity is modified for low collisionality SOL.

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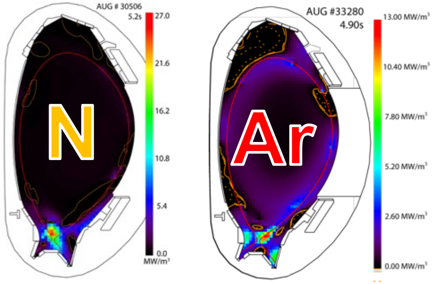
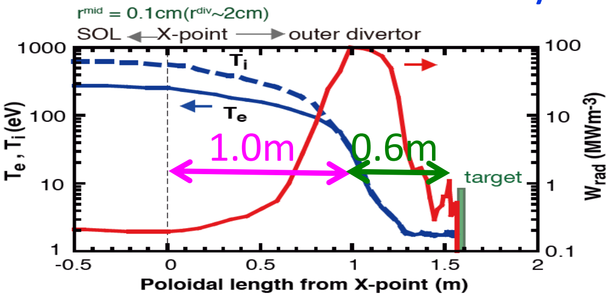
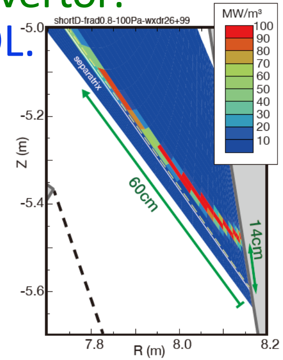
P_{rad}^{div}/P_{heat} >0.6

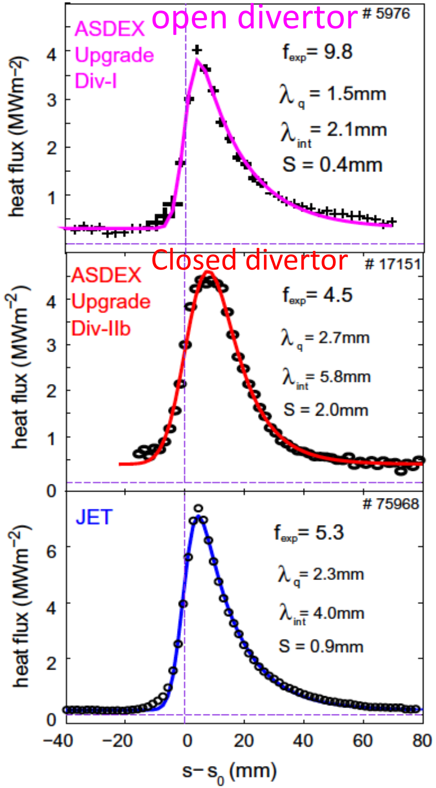






Empirical scaling of heat load profile in attach divertor (Eich's scaling): plasma heat flux is dominat than recombination &radiation

Inter-ELM heat flux profiles in H –mode are fitted by a convolution of exponential and gaussian functions ⇒ Diffusion in SOL (λ_q) and dissipation in divertor (S) are assumed.



Eich-fit function

$$q(\bar{s}) = \frac{q_0}{2} \exp\left(\left(\frac{S}{2\lambda_q}\right)^2 - \frac{\bar{s}}{\lambda_q f_x}\right) \cdot \mathrm{erfc}\left(\frac{S}{2\lambda_q} - \frac{\bar{s}}{S f_x}\right) + q_{BG}$$

Distance from strike point on target: $\bar{s} = s - s_0 = (R_{sep} - R) \cdot f_x$

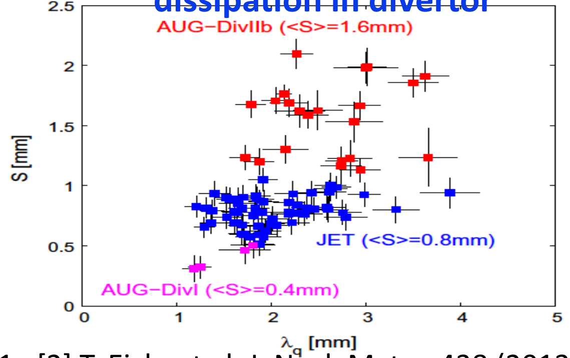
Flux expansion on target: f_x

e-fold length of midplane $q_{//}$-profile (common side): λ_q

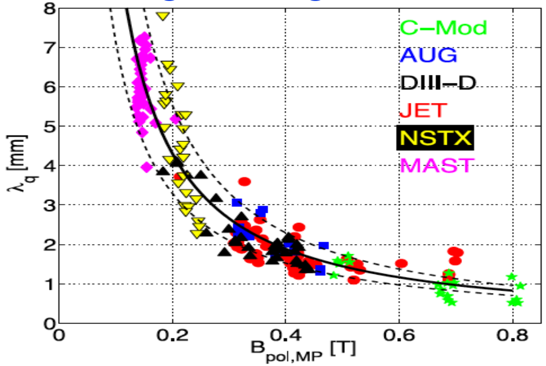
Gaussian function width (private region): S

Average width of integrating q-profile: $\lambda_{int} \cong \lambda_q + 1.64 \cdot S$

"diffusion of SOL heat flux" vs "dissipation in divertor"



Decal length scaling of SOL heat flux



[1] T. Eich, et al. Nucl. Fusion 53 (2013) 093031. [2] T. Eich, et al. J. Nucl. Mater. 438 (2013) S72

Development in simulation code and modelling

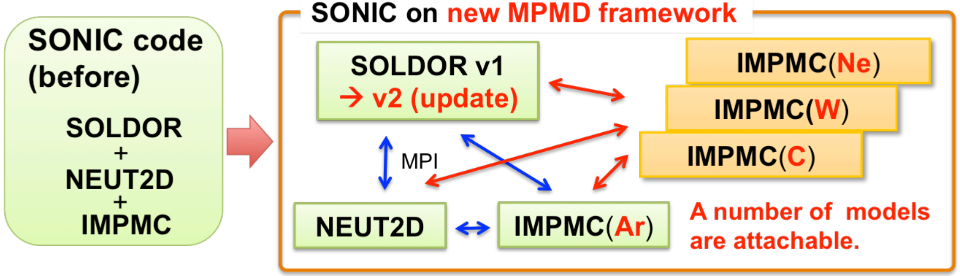
- **Modeling framework using MPMD (Multiple-Program Multiple-Data) approach and MPI (Message Passing Interface) data exchange scheme has been developed for**

(1) Each code can be independently developed, added and replaced with much smaller effort.

(2) Improved numerical efficiency, e.g. number of CPUs used for each code can be arbitrarily adjusted to optimize performance.

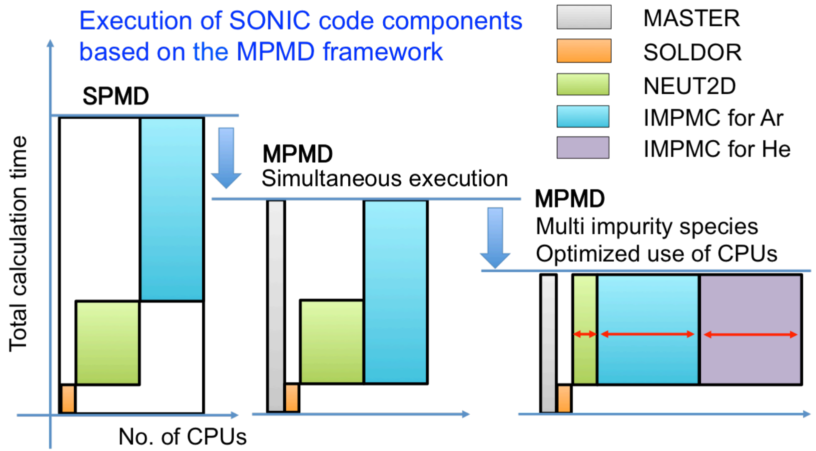
⇒Power exhaust of DEMO divertor, consistent with Ar and He transports, is simulated (2018). Introduction of drift effects is in progress (2018-2020)

Restructured SONIC code with MPMD framework



Each code can be independently developed.

Improved numerical efficiency for multi-imp. cal.



Developments of modelling are in progress to evaluate influences under the DEMO condition:

- Elastic collision model of D-D, D-D2, D2-D2, D-He
- Photon transport (SlimCS: done ⇒ JA DEMO2014)